FIDELITY OF MICHELSON INTERFEROMETRIC AND CONICAL PIEZOELECTRIC ULTRASONIC TRANSDUCERS

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INTRODUCTION

The motivation for this research is our ongoing effort in the development of ultrasonic, waveform-based, materials characterization techniques. Having developed a three-dimensional representation of the elastodynamic Green's Function for anisotropic plates [1], we now seek to verify the applicability of this representation. With elastic properties measurement as our end goal, we also seek a transducer for measurement of theoretically predicted waveforms. Our waveforms typically exhibit a large range in both amplitude (40 to 60 dB) and frequency (20 kHz to 2 MHz). The transducer used must exhibit both high-sensitivity and high-fidelity so that multiple reflections can be detected and identified. In a companion paper we describe a transducer developed at NIST for acoustic emission (AE) studies [2]. In that paper we determine that this transducer has a displacement sensitivity of approximately $5 \times 10^{-17}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ in the 250 kHz to 1 MHz frequency region on aluminum. This transducer appears to be a good candidate for waveform-based materials characterization. In this paper we evaluate this transducer's fidelity by comparing it with both theoretical results and measurements from a path-stabilized, Michelson interferometer. We conclude that the current transducer design does not have sufficient fidelity for waveform-based materials characterization and discuss the reasons for its shortcomings and potential solutions to these problems.

ELASTODYNAMIC GREEN'S FUNCTION FOR ANISOTROPIC PLATES

Two different elastodynamic Green's Functions were used as a baseline for this fidelity study. In addition to Tewary's new delta-function representation for anisotropic plates, Hsu's

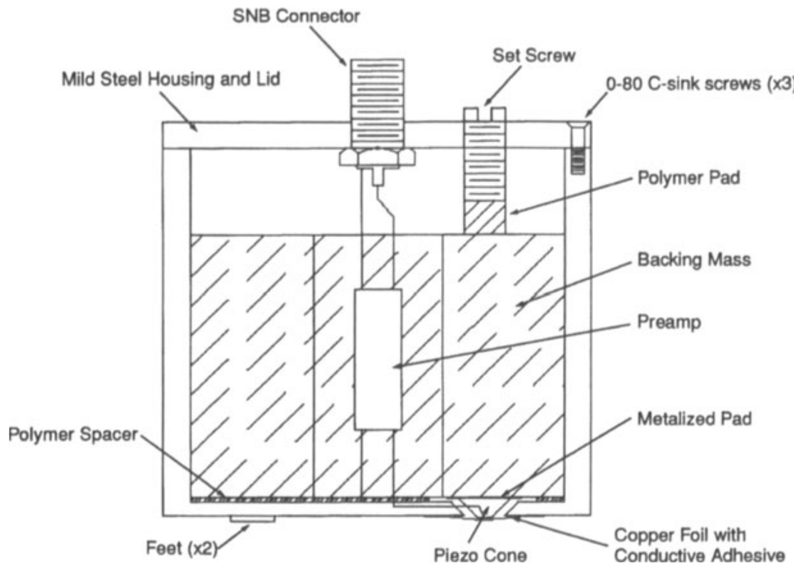

Figure 1. Transducer cross section.

Fourier representation for isotropic plates was also used [3]. While the boundary conditions used in Tewary's calculations prevent the propagation of plate modes, Hsu's computer model includes such displacements. For this reason, the results of the two computations are not identical.

PIEZOELECTRIC DISPLACEMENT SENSOR

The piezoelectric sensor considered in this study is a modification of the Proctor transducer (NIST-SRM #9)[4]. Fortunko and Hamstad [5] have changed the sensor design and added an internal preamplifier. In order to make the transducer practical for field applications they have added a copper wear plate, electromagnetic shielding and a ruggedized case.

In the case of the Proctor transducer, brass is used in for the backing mass because of its similar characteristic impedance to the piezoelectric material (PZT-5A). The backing mass is also shaped such that elastic waves transmitted into it from the piezoelectric element are contained within the mass until they dissipate. The Fortunko-Hamstad transducer uses a cylindrical mass which absorbs the transmitted signal efficiently, but has a substantially different characteristic impedance than the piezoelectric. This impedance mismatch results in reflected signals within the piezoelectric element. Figure 1 shows a cross section of the Fortunko-Hamstad transducer.

MICHELSON INTERFEROMETER

A path-stabilized, polarized optics, Michelson interferometer was used as a primary reference to absolute displacement in this study. A 500 mW (nominal), polarized laser with a wavelength of 1.064 μm was used. The stabilization system consisted of a loop-filter, high-voltage amplifier, and a mirror mounted to a PZT-5H stack with a maximum displacement of 4 μm at +250 V. The loop filter and high-voltage amplifier allowed stabilization to approximately 500 Hz at amplitudes of more than 2 μm. The 10 MHz, high frequency cut-off of the interferometer's response is determined by the 20 MHz sampling rate of the digital storage oscilloscope (DSO) used. It's 500 Hz, low-frequency limit is a result of the active stabilization system. The detector system used in the interferometer is a ±15 volt, reverse-biased, differential circuit similar to that used by Deaton [6] and others. The output of the detection circuit is amplified and recorded on the 12-bit DSO. When incident on a polished aluminum surface, the interferometer exhibits a saturation voltage of approximately 18 V, peak-to-peak. The noise-level of the interferometer is approximately 50 mV. For displacement signals on the order of a few angstroms this gives a signal-to-noise ratio (SNR) of approximately 62 which corresponds to a sensitivity of approximately $1 \times 10^{-15}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$. The laser wavelength used in the interferometer determines the maximum detectable displacement which, for a 1.064 μm wavelength is 0.169 μm. The interferometer, therefore, has a dynamic range of approximately 92 dB in the frequency range from 500 Hz to 10 MHz. The response of the interferometer near its upper displacement limit, however, is nonlinear. The displacements of our signals were well below the nonlinear response region.

MEASUREMENT CONFIGURATION

A large aluminum plate was chosen for this study for both its isotropic elasticity and high reflectivity. The plate had a length and width of 609.9 mm and was 50.8 mm thick. The source used to generate broadband acoustic signals was either a glass capillary break or a lead break at the center of the plate. These two sources were chosen for their close approximation of a step-release and the broad-band frequency content of the resultant acoustic wave [7]. Although the capillary break produced a sharper step-function, the amplitude of the resultant wave was beyond the saturation point of the electronics used in the conical piezoelectric. For this reason data for the capillary are only presented for the interferometer for comparison with theoretical results.

For each measurement, the Fortunko-Hamstad transducer and the interferometer were placed equidistant from the source. A broadband elastic wave signal was generated and then simultaneously detected by the two sensors. The time-dependent waveform from each sensor was recorded on the DSO and stored to floppy disk.

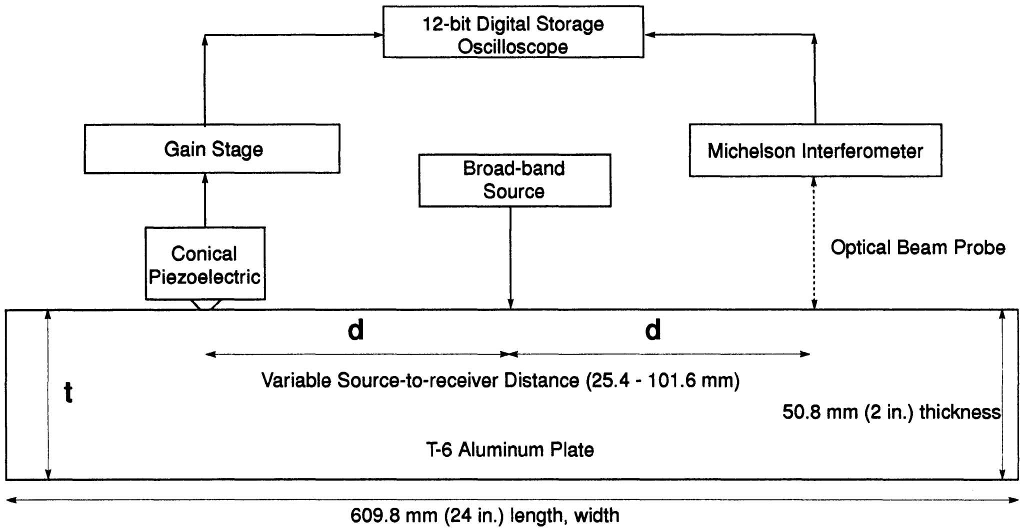

Figure 2. Measurement configuration.

The source-to-receiver distance was varied from 25.4 mm to 101.6 mm. In terms of the ratio of the receiver distance to plate thickness, d/t in Figure 2, the variance was from 0.5 to 2.0. The time-dependent waveforms were then compared.

RESULTS

Figure 3 compares the computed waveforms from both the Tewary and Hsu representations as well as the waveform detected by the Michelson interferometer for a d/t ratio of 0.5. All three are in agreement with the noted absence of the low-frequency, plate modes in the Tewary representation as expected from the boundary conditions mentioned previously.

The measured waveforms from the interferometric and piezoelectric sensors for a d/t ratio of 1.0 are shown in Figure 4. Compared to the interferometric response, the conical piezoelectric exhibits both a resonance with a periodicity corresponding to approximately 450 kHz, and a low-frequency cut-off that appears to correspond to a periodicity of approximately 60 kHz. These factors make it impossible to accurately identify the small-amplitude, multiple reflections of the signal seen in the interferometric waveform. From these results we concluded that, in its current form, the fidelity of the Fortunko-Hamstad transducer is not sufficient for waveform-based materials characterization.

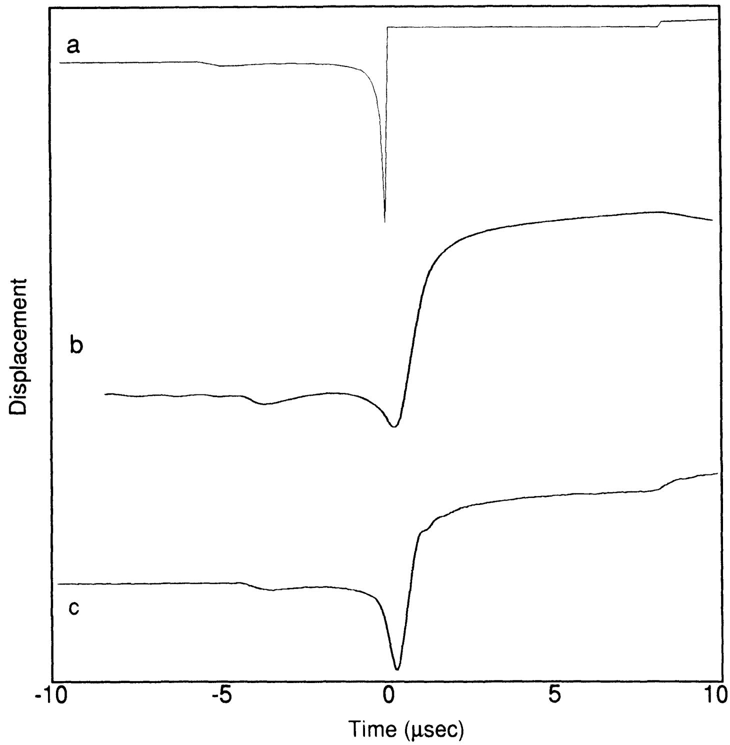

Figure 3. Waveforms calculated using a) Hsu representation, b) Tewary representation and measured using the c) Michelson interferometer.

IDENTIFICATION OF FIDELITY DEGRADATION SOURCES

Figure 5 shows waveforms recorded at a d/t ratio of 1.0 using the NIST-SRM, the NIST-SRM without its preamplifier, and the conical piezoelectric without its preamplifier. These results show that both sensors exhibit a resonance at 450 kHz, but that the notch filter contained within the NIST-SRM preamplifier significantly reduces this resonance. The Fortunko-Hamstad transducer, however, exhibits a substantially larger resonance. We attribute this to both the poorer mechanical impedance match of the PZT-5A to the granite (vs. brass used in the SRM) and the superior attachment process used to bond the piezoelectric to the backing mass in the SRM.

It is also evident from Figure 5 that the removal of the preamplifier electronics from the Fortunko-Hamstad transducer restores the low-frequency response of the sensor. An integrated preamplifier with better low-frequency response would correct this deficiency.

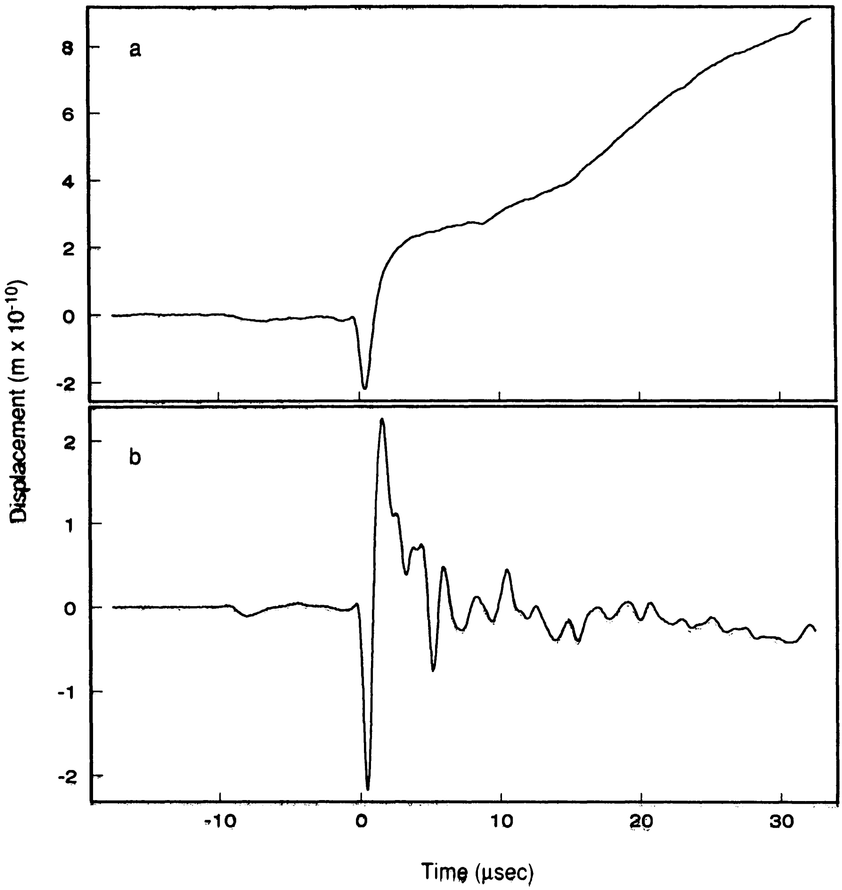

Figure 4. Waveforms from: a) Michelson interferometer and b) Fortunko-Hamstad transducer.

SUMMARY

We have found the Fortunko-Hamstad transducer, designed for AE studies, does not currently have sufficient fidelity for waveform-based materials characterization. We have furth identified the reasons for this sensor's lack of fidelity by comparing it with the NIST-SRM transducer. Work is underway to improve the Fortunko-Hamstad transducer which will result i both a high-sensitivity and a high-fidelity sensor.

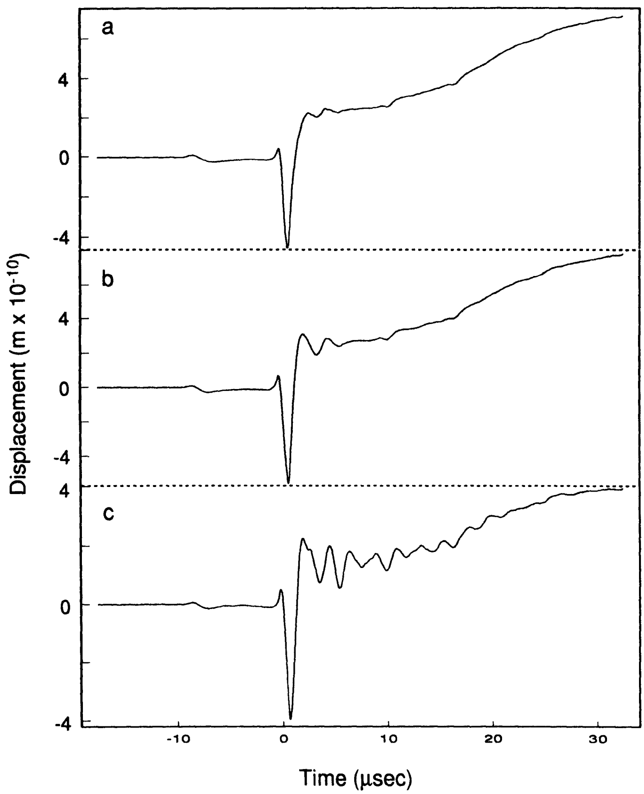

Figure 5. Waveforms from: a) NIST-SRM, b) NIST-SRM without preamplifier and c) Fortunko-Hamstad transducer without preamplifier.

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